THE ARCHIVE OF MECHANICAL ENGINEERING

Vol. XLIX 2002 Number 4

Key words: *vibratory machines, dynamics analysis*

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NEW CONCEPT OF INELIGENT INERTIAL VIBRATOR

The paper presents a new kind of vibrator, called the intelligent vibrator, which is an integrated set of two inert vibrators supplied by asynchronous squirrel-cage motors, equipped with digital control system, the readout system of the position of unbalanced masses, and inverter supply system. The paper presents a model of the prototype of the machine and exemplary run-times.

1. Introduction

The machines that perform the manufacturing or transport process based on the transmission of vibrations of the body of the machine to the machined medium, that is the so-called vibrating machines, are the only, and perhaps the most advantageous form of the realization of the manufacturing process in many branches of industry. The mode of operation of such a machine, which is based on causing intensive polytonal vibrations, often results in the transmission of vibration to the ground, which in turn has a disturbing effect on the surroundings and is detrimental to the health of the people and the condition of edifice. The amplitudes of dynamic forces transmitted to the ground, achieving up to 20kN or even more, together with frequencies up to 100 Hz, are the major source of vibration in industrial plants.

2. Hitherto solutions

The strive to achieve minimal detriment to the surroundings has lead to works on constructing a machine whose working point is above the resonance sphere that is the so called machines of over-resonant type [7]. Most often, in the power transmission systems of these machines, one uses inert vibrators put in motion by three-phase asynchronous motors [1]. During the intermediate

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states (start-up and braking) in the machines of the over-resonant type, there is a sudden increase of vibration connected with the phenomenon of intermediate resonance. A radical solution to the problem of limiting the vibration during the transition through the resonance frequency is constructing and utilizing various types of the so-called self-balancing vibrators realized mechanically [7]. Their functioning is based on the autogenous change of the unbalance of the mass, or the rotating masses of the vibrator, controlled most often by the value of the centrifugal force. However, self-balancing vibrators are themselves very complex mechanical constructions [8], and therefore they cause a considerable increase in the degree of complexity of the machine, and also increase its cost. What is more, the emergency states of the machines with self-balancing vibrators are most often dangerous and may cause malfunction of the suspension system, or even inflict damage to the supporting construction. The material fed mechanically for crushing and dressing, can often be thrown off, and in many cases the staff or to the construction of the edifice could be exposed to danger. It is particularly difficult to use such vibrators in multi-driving systems.

3. The new solution offered by the intelligent vibrator

By using the new type of intelligent vibrator, one can achieve the limitation of vibration in machines of over-resonant type in the intermediate states (start-up and braking), when there is a sudden increase of vibration connected with the phenomenon of intermediate resonance. This vibrator is shown in the block diagram in Fig. 1, was constructed as a compact set of two identical inert vibrators with permanent axis, or pendulous vibrators powered by asynchronous squirrel-cage motors, and is controlled by a digital system. The motors are connected with the elements of the feedback system, which measures the angular position, and directly with the vibrators through placing them on one shaft, or indirectly through mechanical transmissions and possible couplings.

In contrast to other known self-balancing vibrators, the vibrator presented above does not have any mechanical elements responsible for fulfilling the function of limiting the amplitude of generated vibrations. In particular, it does not need neither pawls, nor sliding parts or other mechanical systems, whose functioning is based on the autogenous change of the unbalance of the rotating mass controlled by the value of centrifugal force. Such systems make the mechanical construction of the vibrator more complex, consequently amounting to the main potential source of unserviceability. An electronic control system and a suitable controlling software fulfil those functions.

The principle of operation of the intelligent vibrator discussed in this paper is described below. During the start-up of the machine, the rotating unbalanced masses, consisting of the compact set of two vibrators, are sustained by the control system in such a way as to have the vibrators work in counter-phase. During the start-up and the accompanying transition through the machine's resonant frequency, such a system generates practically no vibrations. When achieving the operating speed (or its vicinity above the resonant frequency), the control system reduces the angle of displacement between the unbalanced masses, thanks to which the vibrator commences to generate the vibrations. Accordingly, during the machine's coasting, the control system first positions the rotating unbalanced masses, which consist of a hybrid of two vibrators, so as to have them work in counter-phase, and then it begins the braking process. As a result, the vibrator practically does not generate any vibrations during the machine's coasting. Moreover, thanks to the use of the inverter supply system, the digital control system, and the compact set of two vibrators, it is possible, if necessary, to flexibly regulate the amplitude of the exciting force together with the machine's working frequency as well as to change the latter.

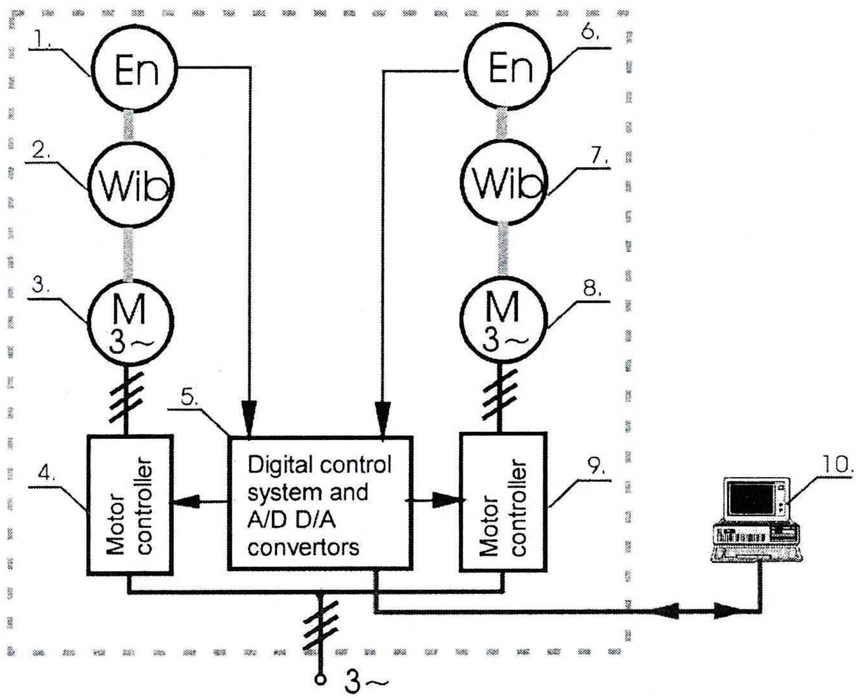

Fig. 1. Vibrator in the block diagram, where: 1 and 6 – optical encoders (the elements of the feedback system), 2 and 7 – vibrators, 3 and 8 – inductive propulsion motors, 4 and 9 – inverter controllers of the motors, 5 – digital control system, 10 – the operator's console; it may possess an alphanumeric display to allow bidirectional communication

This type of vibrator was submited by the author to the Patent Office as an inventory project entitled "A Machine to Generate Mechanical Vibrations with the Unbalanced Masses" and was registered with the number P-344123.

A virtual prototype of the machine powered by the intelligent vibrator was built. It was based on formulas, algorithms, and solutions presented in [2], [4], [5].

4. The virtual prototype of the machine with the intelligent vibrator

For the examination of the virtual prototype, new models have been created which, by means of digital simulation, allow for the analysis of dynamic phenomena in the electromechanical system, i.e. over-resonant vibrating machine. Physical models have been used, the bases of which were the mathematical models presented in [5], [6] describing the mutual interaction between the body of the machine and the power transmission system. By means of digital simulation, those models make it possible to reproduce a number of complicated dynamic phenomena, which are impossible to be examined with the use of the analytic methods. On the other hand, the mentioned phenomena may exert immense influence on the angular velocity of the power transmission system during the coasting, as well as on the amplitudes of the vibrations of the body of the machine in the circum-resonance area [6].
The diagram of machine with inteligent inertial pendulum vibtator is shown in Fig. 2. Equations describing the presented machine are shown below.

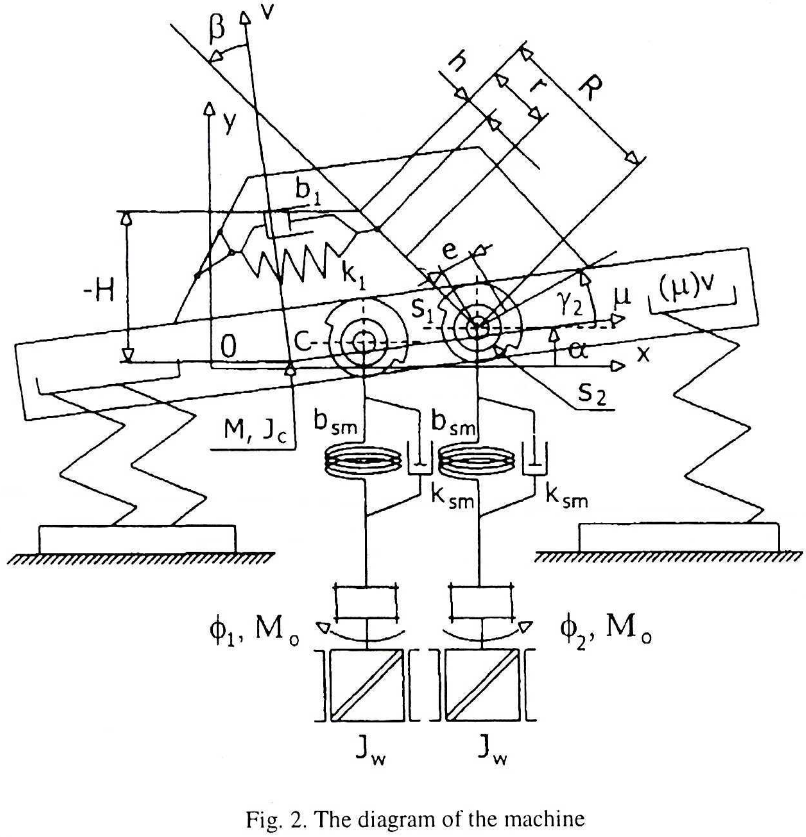

Fig. 2. The diagram of the machine

$$\begin{aligned}
&\left(M+2m_h+2m_n\right)\cdot\ddot{x}+\left[2\left(m_h+m_n\right)H\right]\ddot{\alpha}+\left(m_h r+m_n R\right)\cdot\ddot{\beta}_1+\\
&+\left(m_h r+m_n R\right)\cdot\ddot{\beta}_2-\left[m_n e\sin\left(\gamma_1\right)\right]\cdot\ddot{\gamma}_1-\left[m_n e\sin\left(\gamma_2\right)\right]\cdot\ddot{\gamma}_2=\\
&=jj\Sigma\left[-k_{xx}\left(x-\gamma_i\alpha\right)-k_{xy}\left(y+\mu_i\alpha\right)-k_{x\alpha}\alpha_{|}\right]-\\
&-b_x\dot{x}+m_n e\dot{\gamma}_1^2\cos\left(\gamma_1\right)-b_x\dot{x}+m_n e\dot{\gamma}_2^2\cos\left(\gamma_2\right);
\end{aligned}\tag{1}$$

$$\begin{aligned}
&\left(M+2m_h+2m_n\right)\cdot\ddot{y}+[m_n e\cos(\gamma_1)]\ddot{\gamma}_1+[m_n e\cos(\gamma_2)]\ddot{\gamma}_2=\\
&=jj\Sigma[-k_{yx}(x-\gamma_i\alpha)-k_{yy}(y-\mu_i\alpha)-k_{y\alpha}\alpha]-b_y\dot{y}+\\
&+m_n e\cdot\dot{\gamma}_1^2\sin\left(\gamma_1\right)+m_n e\cdot\dot{\gamma}_2^2\sin\left(\gamma_2\right);
\end{aligned}\tag{2}$$

$$\begin{aligned}
&\left[2\left(m_h+m_n\right)H\right]\ddot{x}+\left[I_c+2\left(m_h+m_n\right)H^2\right]\ddot{\alpha}+\left[\left(m_h r+m_n R\right)H\right]\ddot{\beta}_1+\\
&+\left[\left(m_h r+m_n R\right)H\right]\ddot{\beta}_2-\left[m_n eH\cdot\sin\left(\gamma_1\right)\right]\ddot{\gamma}_1-\left[m_n eH\cdot\sin\left(\gamma_2\right)\right]\ddot{\gamma}_2=\\
&=jj\Sigma-\{k_{\alpha x}\left(x-\gamma_i\alpha\right)+k_{\alpha y}\left(y-\mu_i\alpha\right)+k_{\alpha\alpha}\alpha+\mu_i[k_{yx}\left(y-\gamma_i\alpha\right)+\\
&+k_{yy}\left(y-\mu_i\alpha\right)+k_{y\alpha}\alpha]-\gamma_i[k_{xx}\left(x-\gamma_i\alpha\right)+k_{xy}\left(y-\mu_i\alpha\right)+k_{x\alpha}\alpha]\}\\
&-b_\alpha\dot{\alpha}+m_n eH\dot{\gamma}_1^2\cos\left(\gamma_1\right)+m_n eH\dot{\gamma}_2^2\cos\left(\gamma_2\right)+b_1h^2(\dot{\beta}_1-\dot{\alpha})+\\
&+k_1h^2(\beta_1-\alpha)+b_1h^2(\dot{\beta}_2-\dot{\alpha})+k_1h^2(\beta_2-\alpha);
\end{aligned}\tag{3}$$

$$\begin{aligned}
&2(m_h r+m_n R)\ddot{x}+[2(m_h r+m_n R)H]\ddot{\alpha}+(m_h r^2+m_n R^2+\\
&+I_h)\ddot{\beta}_1+(m_h r^2+m_n R^2+I_h)\ddot{\beta}_2-[m_n Re\cdot\sin\left(\gamma_1\right)]\ddot{\gamma}_1\\
&-[m_n Re\cdot\sin\left(\gamma_2\right)]\ddot{\gamma}_2=m_n Re\dot{\gamma}_1^2\cdot\cos\left(\gamma_1\right)+m_n Re\dot{\gamma}_2^2\cdot\cos\left(\gamma_2\right)-\\
&-b_1h^2(\dot{\beta}_1-\dot{\alpha})-k_1h^2(\beta_1-\alpha)-b_1h^2(\dot{\beta}_2-\dot{\alpha})-k_1h^2(\beta_2-\alpha);
\end{aligned}\tag{4}$$

$$\begin{aligned}
&-[m_n e\cdot\sin\left(\gamma_1\right)]\ddot{x}+[m_n e\cdot\cos\left(\gamma_1\right)]\ddot{y}-m_n eH\cdot\sin\left(\gamma_1\right)\ddot{\alpha}-\\
&-m_n eR\cdot\sin\left(\gamma_1\right)\ddot{\beta}_1+(I_n+m_n e^2)\ddot{\gamma}_1=\\
&=k_{sm}(\gamma_1-\varphi_1\frac{d_1}{d_2})-b_{sm}(\dot{\gamma}_1-\dot{\varphi}_1\frac{d_1}{d_2})-b_o\gamma_1^2\mathrm{sgn}(\dot{\gamma}_1-\dot{\beta}_1);
\end{aligned}\tag{5}$$

$$
\begin{gathered}
-m_n e \cdot \sin\left(\gamma_2\right)\ddot{x} + m_n e \cdot \cos\left(\gamma_2\right)\ddot{y} - m_n eH \cdot \sin\left(\gamma_2\right)\ddot{\alpha} - \\
-m_n eR \cdot \sin\left(\gamma_2\right)\ddot{\beta}_2 + (I_n + m_n e^2)\ddot{\gamma}_2 = \\
= -k_{sm}(\gamma_2 - \varphi_2 \frac{d_1}{d_2}) - b_{sm}(\dot{\gamma}_2 - \dot{\varphi}_2 \frac{d_1}{d_2}) - b_o \dot{\gamma}_2^2 \operatorname{sgn}(\dot{\gamma}_1 - \dot{\beta}_2);
\end{gathered} \tag{6}
$$

$$
\begin{gathered}
\left[I_w + I_1 + I_2 \frac{d_1^2}{d_2^2} \right] \ddot{\varphi}_1 = \\
= -k_{sm}\left(\varphi_1 \frac{d_1}{d_2} - \gamma_1\right)\frac{d_1}{d_2} - b_{sm}\left(\dot{\varphi}_1 \frac{d_1}{d_2} - \dot{\gamma}_1\right)\frac{d_1}{d_2} + M_{el_1} - M_o \operatorname{sgn}\left(\dot{\varphi}_1\right);
\end{gathered} \tag{7}
$$

$$
\begin{gathered}
\left[I_w + I_1 + I_2 \frac{d_1^2}{d_2^2} \right] \ddot{\varphi}_2 = \\
= -k_{sm}\left(\varphi_2 \frac{d_1}{d_2} - \gamma_2\right)\frac{d_1}{d_2} - b_{sm}\left(\dot{\varphi}_2 \frac{d_1}{d_2} - \dot{\gamma}_2\right)\frac{d_1}{d_2} + M_{el_2} - M_o \operatorname{sgn}\left(\dot{\varphi}_2\right);
\end{gathered} \tag{8}
$$

$$
\operatorname{Re}\dot{\Phi}_{s1} = -a_s\left(\operatorname{Re}\Phi_{s1} - \frac{1}{k_w}\operatorname{Re}\Phi_{w1}\right) + \operatorname{Re}U_1; \tag{9a}
$$

$$
\operatorname{Im}\dot{\Phi}_{s1} = -a_s\left(\operatorname{Im}\Phi_{s1} - \frac{1}{k_w}\operatorname{Im}\Phi_{w1}\right) + \operatorname{Im}U_1; \tag{9b}
$$

$$
\operatorname{Re}\dot{\Phi}_{w1} = -a_w\left(\operatorname{Re}\Phi_{w1}\frac{k_s}{k_w} - \frac{1}{k_w}\operatorname{Re}\Phi_{s1}\right) - \dot{\varphi}_1 \, ip \operatorname{Im}\Phi_{w1}; \tag{10a}
$$

$$
\operatorname{Im}\dot{\Phi}_{w1} = -a_w\left(\operatorname{Im}\Phi_{w1}\frac{k_s}{k_w} - \frac{1}{k_w}\operatorname{Im}\Phi_{s1}\right) - \dot{\varphi}_1 \, ip \operatorname{Re}\Phi_{w1}; \tag{10b}
$$

$$
M_{el_1} = -\frac{2M_u \omega_o^2 p}{I_w}\left(\operatorname{Re}\Phi_{s1}\operatorname{Im}\Phi_{w1} - \operatorname{Im}\Phi_{s1}\operatorname{Re}\Phi_{w1}\right)I_w; \tag{11}
$$

$$\operatorname{Re}\dot{\Phi}_{s2} = -a_s\left(\operatorname{Re}\Phi_{s2} - \frac{1}{k_w}\operatorname{Re}\Phi_{w2}\right) + \operatorname{Re}U_2; \tag{12a}$$

$$\operatorname{Im}\dot{\Phi}_{s2} = -a_s\left(\operatorname{Im}\Phi_{s2} - \frac{1}{k_w}\operatorname{Im}\Phi_{w2}\right) + \operatorname{Im}U_2; \tag{12b}$$

$$\operatorname{Re}\dot{\Phi}_{w2} = -a_w\left(\operatorname{Re}\Phi_{w2}\frac{k_s}{k_w} - \frac{1}{k_w}\operatorname{Re}\Phi_{s2}\right) - \dot{\varphi}_2\, ip\operatorname{Im}\Phi_{w2}; \tag{13a}$$

$$\operatorname{Im}\dot{\Phi}_{w2} = -a_w\left(\operatorname{Im}\Phi_{w2}\frac{k_s}{k_w} - \frac{1}{k_w}\operatorname{Im}\Phi_{s2}\right) - \dot{\varphi}_2\, ip\operatorname{Re}\Phi_{w2}; \tag{13b}$$

$$M_{el_2} = -\frac{2M_u\omega_o^2 p}{I_w}\left(\operatorname{Re}\Phi_{s2}\operatorname{Im}\Phi_{w2} - \operatorname{Im}\Phi_{s2}\operatorname{Re}\Phi_{w2}\right)I_w; \tag{14}$$

where:

- x, y, α – vertical and horizontal coordinates of the centre of mass and the yaw angle from the level of the body of the machine,
- β – angular displacement of pendulum measured in relation to the level,
- φ_1 – angle of rotation of rotor of the first motor,
- φ_2 – angle of rotation of rotor of the second motor,
- Φ_{s1}, Φ_{w1} – flux linkages of stator and rotor divided by the value of the voltage of the first motor,
- Φ_{s2}, Φ_{w2} – flux linkages of stator and rotor divided by the value of the voltage of the first motor,
- γ_1 – angle of rotation of first vibrator measured in relation to the level,
- γ_2 – angle of rotation of second vibrator measured in relation to the level,
- M – mass of machine body,
- m_h – mass of the pendulum,
- m_n – unbalanced mass of vibrator,
- I – moment of inertia of the power transmission system reduced to the shaft of vibrator with the central moment of inertia of vibrator,
- I_c – central moment of inertia of machine body,
- I_h – central moment of inertia of pendulum,
- I_n – central moment of inertia of unbalanced mass,
- I_w – central moment of inertia of rotor of the motor,

I_1, I_2 – central moment of inertia of belt pulleys,
H – distance between the axis of the pendulum and the centre of mass of the body measured vertically; with the sign (-) when the axis of the pendulum is above the centre of mass of the body,
H – distance of the fixing point of the stabilizing system together with pendulum and its axis of rotation,
E – eccentricity of vibrator,
R – distance between the axis of rotation of the pendulum and the axis of the vibrator,
R – distance between the centre of mass of the pendulum and its axis of rotation,
d_1, d_2 – diameters of belt pulleys,
μ_i, ν_i – coordinates of the fixing points of the units of suspension springs to the body of the machine in relative, central coordinate system $C_{\mu\nu}$,
k_1, b_1 – elasticity and viscotic damping coefficients of the pendulum stabilizing system,
k_{sm}, b_{sm} – elasticity and rotation damping coefficients for the coupling,
α_s, α_w – proportional parameters of the model of the motor,
jj – number of elastic elements in the unit,
M_o – moment of inertia of the power transmission system reduced to the shaft of the vibrator,
M_u – pull-out torque,
M_{el} – electromagnetic moment working on the rotor of motor,
ω_o – angular velocity of the supply voltage (of the network),
I – position of the belt transmission between the motor and the rotor, $i=\omega_{motor}/\omega_{vibrator}$, that is d_2/d_1,
P – number of pairs of poles of the asynchronous machine,
U – normalized (divided by the reference voltage) required power supply voltage,
b_o – coefficient of resistance in bearings.

A converter system was used for the realization of the control system of the virtual prototype of the machine. The aim of the use of the converters was the regulation of the electric drive according to the programme of its function. It was assumed that the system should realize braking through the reduction of the supply frequency and the rms value of the supply voltage. This method requires the use of the inverter system. This type of system has a vital advantage, which consists in the possibility of controlling the action of the power transmission system in a wide range during braking. It has also an important practical feature, namely the possibility of bidirectional transmission of the electric energy without the use of an additional back rectifier. The use of such systems is advisable in drives, which require frequent and precise regulation of the angular velocity, as well as frequent braking. What is more, in practice the system may allow to eliminate the transmission from the construction of the machine. It was assumed that the digital control system will realize the control algorithms described above. Optical encoders have been used in the feedback system. They have been placed (combined mechanically) on the propeller shafts. They give a direct digital display of the angular position, and the angular velocity is determined by numerical integration done by the computer control system.

Exemplary time functions of vertical vibrations y are shown below. The upper diagram presents the results for a machine with an ordinary vibrator, and the lower one – with the intelligent vibrator. The results fully confirm the correctness of the assumptions and prove that the intelligent vibrator works correctly, as it has been expected.

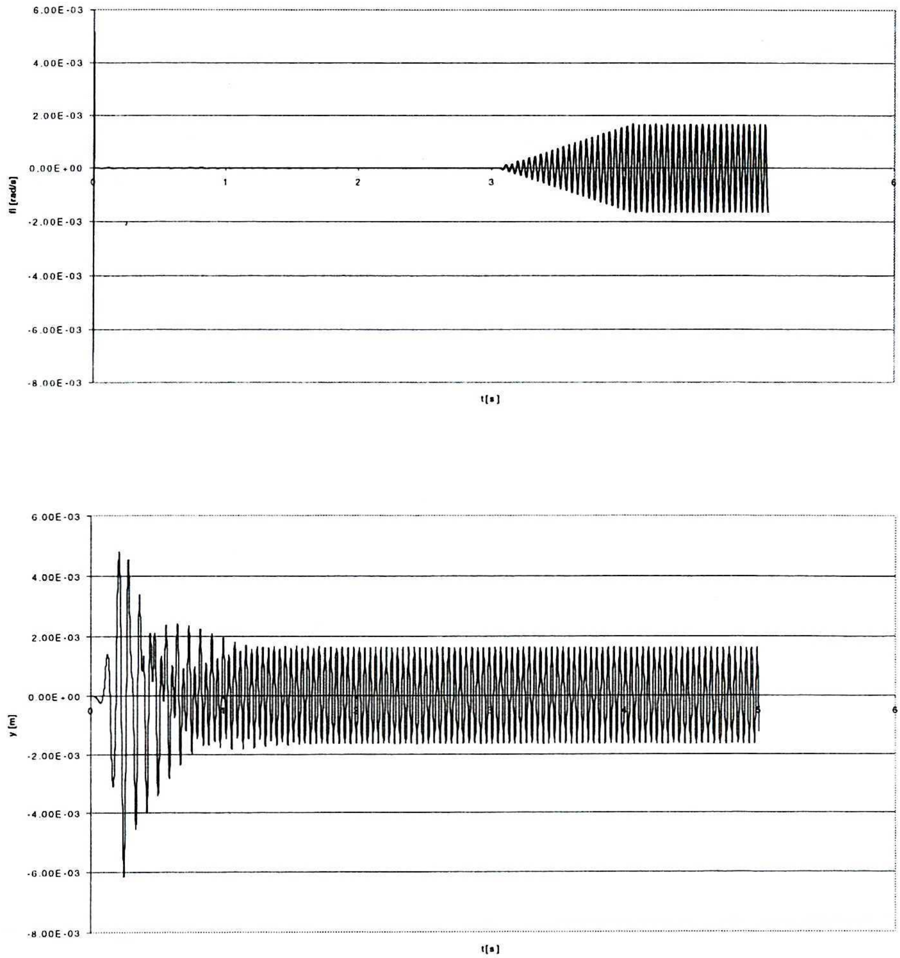

Fig. 3. Time functions of displacements of vertical vibrations - amplitude

With the use of the presented intelligent vibrator, the phenomenon of intermediate resonance practically does not exist. Therefore, the results presented above fully confirm the correctness of the assumptions and prove that the work of the intelligent vibrator is correct, as it has been expected. They provide reduction of the maximum amplitude in the time of horizontal start-up by about 94%, and vertical – by more than 99%. According to the expectations, the detrimental effects connected with the increase of the vibration amplitude have been almost entirely eliminated.

It was possible thanks to the fact that during the start-up and the accompanying transition through the resonance frequency of the machine, the intelligent vibrator generates virtually no vibrations. After achieving the operating speed (or its vicinity above the resonance frequency), the control system reduces the displacement angle between the unbalanced masses, thanks to which the vibrator starts to generate the vibrations.

Accordingly, during the machine's coasting, the control system first sets the rotating unbalanced masses in the compact set of two vibrators, in such a way as to have the vibrators work in counter-phase, and only then it begins braking. The result of this action is that the vibrator generates virtually no vibrations during the machine's coasting.

Manuscript received by Editorial Board, May 16, 2002;
final version, November 30, 2002.

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Nowego typu inteligentny wibrator inercyjny

S t r e s z c z e n i e

W pracy przedstawiono nowego typu wibrator przeznaczony do napędu maszyn wibracyjnych, w szczególności maszyn nadrezonansowych. Wibrator taki zbudowany jest jako zintegrowany zestaw dwóch jednakowych wibratorów inercyjnych napędzanych asynchronicznymi silnikami klatkowymi i działa w oparciu o cyfrowy układ sterowania. W układzie sprzężenia zwrotnego wykorzystuje się pomiar położenia kątowego mas niewyważonych. Omawiany wibrator inteligentny stanowi zatem urządzenie mechatroniczne, w którym zintegrowane są elementy mechaniczne, elektroniczne i układ sterowania komputerowego wraz z oprogramowaniem.

Zaprezentowano model obliczeniowy prototypu maszyny wibracyjnej napędzanej takim wibratorem i pokazano uzyskane przykładowe przebiegi czasowe.